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DETECTION OF LACK OF FUSION USING OPAQUE ADDITIVES PHASE II

by

J. L. Cook

May 1973

Prepared under Contract NAS8-28708
for the period
1 November to 30 April 1973
by
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

There are currently two major problems in welded aluminum spacecraft structure. These are (1) reliable nondestructive inspection for incomplete weldment penetration and (2) the rapid oxidation of aluminum surfaces left exposed to the atmosphere. Incomplete-penetration defects are extremely hard to detect and can lead to catastrophic failure of the structure. The moisture absorbed by aluminum oxide on the surface can cause weldment porosity if the surface is not cleaned carefully immediately before welding.

The approach employed in this program to solve both problems was to use a copper coating to prevent oxidation of the aluminum and as an opaque additive in the weldment to enhance x-ray detection in the event of incomplete penetration.

In the first phase of the program, it was determined that vacuum vapor-deposited coatings were superior to plasma-sprayed coatings. In the Phase II effort, the objectives were to determine if the plasma-sprayed copper coatings could protect the aluminum surface for a period of 60 days, correlate the actual location of transition between incomplete penetration and full penetration weldment with that shown on the x-ray film, assess the capability of ultrasonic Delta-scan for detecting incomplete weldment penetration and further substantiate the retention of acceptable mechanical properties after the addition of the copper in the weldment. In addition, the feasibility of peen plating was to be determined as a means of applying copper to an aluminum surface.

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It was determined that the 60-day storage of the copper coated specimens had no effect upon the weldments. The x-ray film does provide a very accurate indication of the transition from incomplete penetration to full penetration weldment. Ultrasonic Delta-scan is not suitable for detection of tight incomplete penetration defects, whether or not copper is present as an additive. Peen plating was only marginally successful in depositing copper on aluminum, and additional work is needed for practical application. The mechanical tests indicated that there was little or no change in properties because of the added copper.

The concept of the opaque additive was proved very effective. Promise of long-term protection of aluminum surfaces was indicated by successful storage of coated samples for 60 days. Additional effort in the area of copper application has indicated peen plating as a viable method for further study. Continued effort is necessary to further develop this means of applying the copper in a manufacturing environment.

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Section 1
INTRODUCTION

Welded aluminum alloy structure has been used extensively in current generation spacecraft and is expected to be used for future space shuttle vehicles and propellant tankage. At one time weldment porosity was a major problem in production of aluminum weldments. This porosity was attributed to moisture absorbed by the aluminum oxide which forms on the surface before welding. This problem occurs because of formation of the moisture-absorbing oxide in storage. This oxidation process is very rapid, and cleaning procedures as shortly before welding as is practical are necessary to improve the probability of making a porosity-free weld.

Another problem of serious concern, particularly in welding thick-section butt joints from both surfaces, is incomplete penetration of the weldment. When this condition occurs, a knife-edge crack or separation is left unfused in the weld joint. Such a stress concentrator in a weldment can produce catastrophic failure during proof testing or service of large cryogenic propellant tankage. Previous MDAC experience on the S-IVB program demonstrated that incomplete penetration of a weldment could result in failure of a vessel. One such defect led to failure during a hydrostatic pressure test. Considering the cost of such vehicles as the S-IVB, and particularly of the larger tankage anticipated for the Space Shuttle program, any reasonable means of averting such failure must be explored.

It has been shown that a lack-of-penetration defect is perhaps one of the most difficult to detect by conventional nondestructive inspection techniques. Because of high residual compressive stresses present in weldments containing this type of defect, it is possible for x-ray and ultrasonic inspection techniques to miss such defects (Reference 1). Such defects are so tight that they cannot entrap a sensitive fluorescent penetrant, even when they are exposed to the surface and visually apparent.

The objective of this program is to develop a means of solving the problems of surface oxidation and detection of lack-of-penetration defects. The means to this solution lies in coating the aluminum surfaces to be protected with an x-ray-opaque metal such as silver or copper. In this way, the formation of moisture-absorbing aluminum oxide may be stopped. Furthermore, any protective coating remaining in an area of incomplete weld penetration would be clearly evident on the x-ray of the weldment.

To meet the objective, the effort was divided into two phases. The objective of Phase I was to select a technique that would provide a thin but impervious coating of copper. That work has been completed and has been reported (Reference 2).

The objectives of Phase II of this program were:

A. Determine if a vacuum vapor-deposited coating of copper 5.08×10^{-6} m (2×10^{-4} in.) thick could adequately protect the aluminum surface for a minimum of 60 days.
B. Determine how accurately the x-ray film can indicate the location of transition between incomplete penetration and full penetration aluminum weldment.
C. Assess the capability of ultrasonic Delta-scan techniques to detect tight incomplete penetration defects.
D. Substantiate the Phase I results indicating that the added copper does not significantly affect the weldment mechanical properties.
E. Determine the practicality of peen plating as a means of applying copper to an aluminum surface.

This report presents the technical approach, the technical efforts, and results of the Phase II effort.

Section 2
TECHNICAL APPROACH

The approach taken in this program was to develop a suitable thin, moisture-free, continuous copper coating for application to 2219 aluminum. The alloy 2219 was selected because of its current and anticipated future use in major spacecraft structures.

There were several factors which had to be considered in this approach.

A. Covering and protective capability of the coating.
B. Effect of coating on the composition of the weldment.
C. Minimum thickness of coating necessary to provide x-ray indication of lack of weld penetration.

Copper was selected for several reasons. It has an x-ray absorption coefficient (Reference 3) very much greater than that of aluminum, and therefore is easily detectable in x-rays of aluminum. Copper is also contained in many aluminum alloys—approximately 6 percent in 2219. Therefore, minor additions of copper would not be detrimental to alloy composition.

In the Phase I effort, an attempt was made to understand the factors listed above and to select a specific deposition technique for further effort. Two copper deposition techniques were employed: (1) plasma spray and (2) vacuum vapor deposition. Both techniques were felt to be potentially capable of depositing a thin layer of copper of sufficient density to protect the aluminum surface.

To achieve the objectives of Phase II as stated in Section 1, Introduction, 40 test panels of 2219-T87 aluminum were copper coated on one edge abutting surfaces during welding) and subsequently held in storage for 60 days. The copper was deposited approximately 5.08×10^{-6}-m (2×10^{-4}-in.) thick by vacuum vapor deposition which proved very successful in the Phase I effort (Reference 2).

Upon completion of the 60-day storage time, the panels were welded together by the same technique and parameters as employed in Phase I (Reference 2).

In a parallel effort, 20 panels were prepared without a copper coating and welded to make 10 welded specimens. Both of these uncoated and the copper-coated panels were welded in the same manner, with a zone of tapered incomplete penetration for approximately 0. 15 m (6 in.) at one end of the 0. 61 m (24 in.) long panel.

Nondestructive testing of the welded test panels consisted of x-ray and ultrasonic Delta-scan methods. Mechanical tests included tensile and bend tests to determine the effect of copper on weldment properties. In addition, peen plating was investigated and experiments conducted with several test samples.

Altogether, the Phase II effort was aimed at verifying the effect of a copper additive on the nondestructive tests and on the mechanical properties of the weldments, and at determining the feasibility of peen plating as a means of applying copper to the aluminum.

Section 3
PROCEDURES AND RESULTS

3.1 MATERIAL

Nine plates of 2219-T87 aluminum alloy were procured from stock for the various panels and specimens. These plates were 0.127-m (0.5-in.) thick. Seven of these plates were 0.610-m (24-in.) wide and 1.829-m (72-in.) long, and two plates were 0.219-m (48-in.) wide and 3.048-m (120-in.) long. A cutting plan (Figure 1) was developed to provide the necessary samples for both phases of the program.

Sixty panels, 0.152 by 0.610 by 0.127-in. thick (6 by 24 by 0.5-in. thick) were machined for the Phase II effort. Twenty of these were reserved for control weldments which would contain no copper additive. The remaining 40 were to be copper coated. In each case, half of each group had been cut so that the weldment would be transverse to the plate rolling direction and half were cut so that the weldment would be parallel to the plate rolling direction.

3.2 COPPER DEPOSITION

Copper was applied to one long edge of each of the 40 panels by vacuum vapor deposition. The procedure employed was identical to that in the Phase I effort (Reference 2). The coating thickness was approximately 5.08×10^{-6}m (2×10^{-4} inch).

Some trouble was encountered in the coating procedure. Several panels exhibited peeling and spallation of the copper coating, and it was decided to strip all copper and repeat the procedure. While the exact cause of the peeling was not determined, it was probably a cleaning problem. Special care was exercised during the second coating sequence in both the chemical cleaning and the glow discharge procedure. After the second coating, all panels except two appeared to have a satisfactory coating. The two displayed some small blistering near one end. It was decided not to attempt

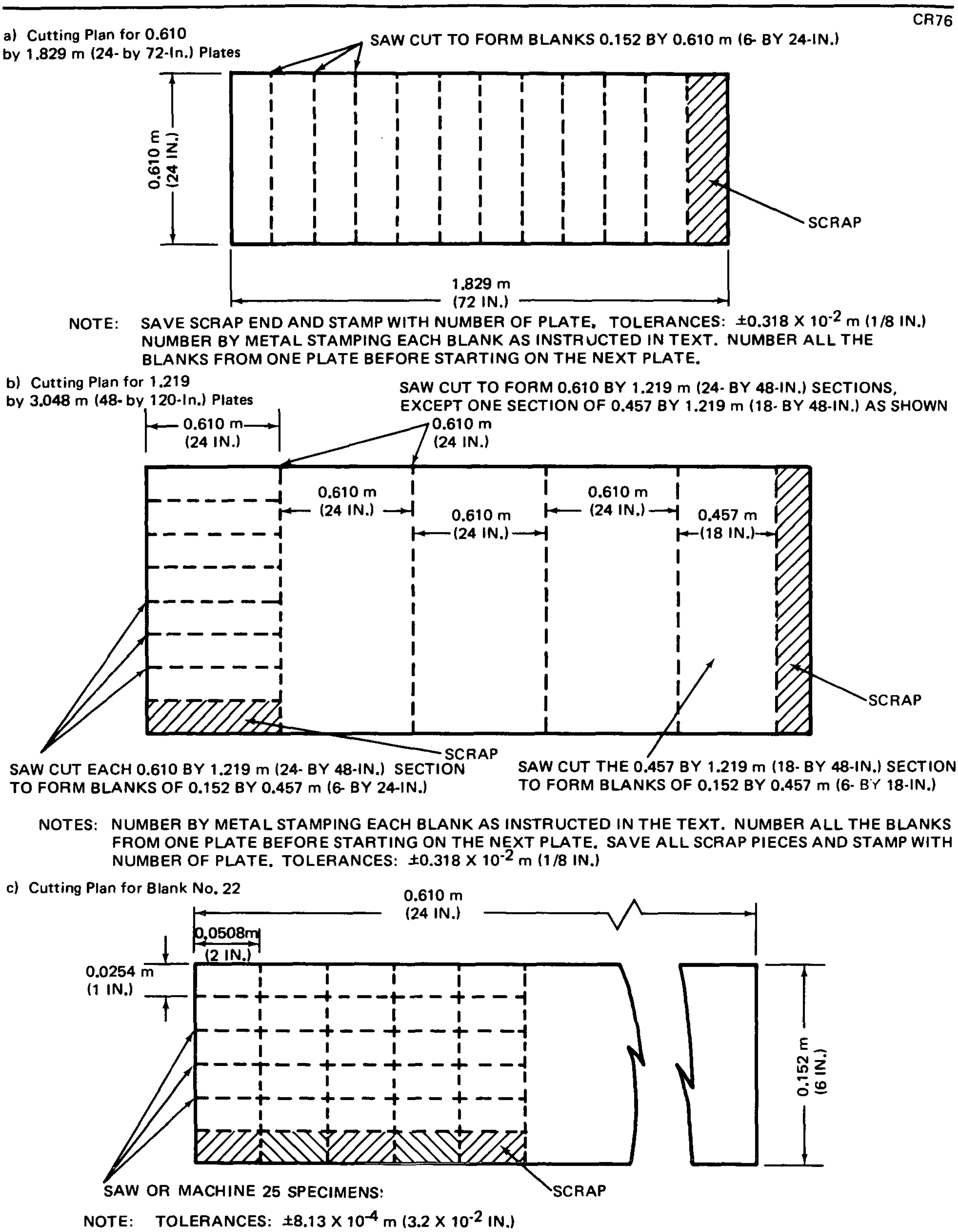


Figure 1. Cutting Plans for Aluminum Plates

further stripping and recoating on these two panels since the blistered areas were near the ends of the panels and could be positioned away from the incomplete penetration zone during welding.

3.3 WELDING

The welding effort on Phase II consisted of the welding of 10 uncoated and 20 copper-coated panels. Half of the panels in each lot were welded with the rolling direction parallel to the weld joint, and the remaining were welded perpendicular to the rolling direction.

The tapered incomplete penetration gas metal arc (GMA) numerically controlled welding procedure developed in Phase I (Reference 2) was used to weld all panels in Phase II. This was accomplished by using the same punched tape containing the previously developed welding parameters and travel speed changes on the same equipment with 2319 Al filler wire and He-A-O_2 shielding gas mixture.

The uncoated panels were cleaned prior to welding in exactly the same manner as the control panels in Phase I. The surfaces on the joint edge were wiped with a clean, lint-free cloth dampened with acetone. They were then etched with a tri-etch method (chromic, nitric, and hydrofluoric acids) for a minimum of 5 minutes, agitating frequently. After water rinsing, the edges were neutralized with a solution of sulfuric acid and sodium dichromate and rinsed with deionized water until a pH value of 5.0 to 8.0 was reached. After drying, the top and bottom surfaces adjacent to the edge were mechanically cleaned with a power-driven, small-bristle, stainless steel brush. Then the faying surface was draw-filed with a Vixen file, at the same time removing any burrs from the corners. The assembled joint was inspected with a black light for any remaining organic contaminants just prior to welding.

The air in the environmental enclosure surrounging the welding equipment was examined for particulate matter. It was found to contain no more than 6,179 particles per cubic meter (175 particles per cubic foot) larger than 10 microns in diameter. This compares with a level of 21,186 particles per cubic meter (600 particles per cubic foot), 10 microns or larger, allowed before welding the Saturn S-IVB vehicle.

The dew point of the shielding gas was tested as it exited from the welding torch and was found to have only 10 ppm (parts per million) of water vapor, well below the 17 ppm permitted for the Saturn S-IVB welding.

After welding, the control panels were mechanically shaved to within 2.54×10^{-4} m (1×10^{-2} inch) of the panel surface on both sides, and then submitted for nondestructive inspection.

The copper-coated panels were held in storage for 60 days between the coating and welding operations. Each panel was wrapped in an unsealed polyurethane bag and the entire 40 panels were kept in wooden boxes stored in the welding laboratory.

Just prior to welding, each numbered set of panels was removed from storage and power wire brushed as an assembly in a band approximately 0.10-m (40in.) wide on both surfaces to prevent disturbing the copper-coated faying surfaces. Upon disassembly, the corners of the specimens were broken with a Vixen file, and the coating wiped with a clean, lint-free cloth dampened with acetone. The panels were then assembled in the weld fixture and the joint was black-light inspected just prior to welding on each side. The environment was again sampled for particulate matter and was found to be the same as before. The shielding gas employed to weld these panels was from the same gas cylinder used to weld the uncoated panels.

The 20 panels were welded satisfactorily except for a few minor problems. The 20 panels with comments on problems and the welding parameters are listed in Table 1.

Panels 3738 through 103104 were welded on the 61st day after coating with copper. The welding characteristics were excellent with the exception of the first pass on panel 3738. The arc instability experienced at the end of the tapered region was later found to be the result of an excessively short cup-to-work distance setting, which caused an overall increase of arc current. The cavitated region was ground smooth with a rotary file and filled with 2319 filler wire, using manual GTA welding with AC polarity. After cooling to room temperature, the second side was welded quite successfully with only a slight disturbance occurring opposite the point of repair.

Table 1

COMMENTS ON 20 WELDED PANELS WITH COPPER ADDED

Panel No.	Pass No.	Operational Characteristics
3738	1	Gouged at end of taper—manually GTA repaired.
	2	OK except slight disturbance opposite repair.
3940	1	OK
	2	OK
4142	1	OK
	2	OK
4344	1	OK
	2	OK
4546	1	OK
	2	OK
4748	1	OK
	2	OK
4950	1	Slight arc disturbance at end of taper.
	2	OK
5152	1	OK
	2	OK
5354	1	OK
	2	OK
5556	1	OK
	2	OK
99100	1	OK
	2	OK
101102	1	OK
	2	OK
103104	1	OK
	2	Gouged first 3.5 inches
105106	1**	OK
	2**	Gouged first 4.0 inches
107108	1**	OK
	2*	OK

Table 1

COMMENTS ON 20 WELDED PANELS WITH COPPER ADDED (Continued)

Panel No.	Pass No.	Operational Characteristics
109110	1**	OK
	2*	OK
111112	1**	Gouged first 5.0 inches
	2**	Gouged between first 1 to 3.5 inches
113114	1**	Gouged between first 1 and 2 inches
	2**	OK
115116	1	Gouged between first 1 and 2 inches
	2*	OK
117118	1**	OK
	2*	Slight disturbance at 2 inches from start

Tape No. - 92972 mylar
Torch lead angle - 0.087 radian (5 deg) for panels 3738 through 103104
0.105 radian (6 deg) for passes**
0.070 radian (4 deg) for passes*
Gas type and flow - He-A-O_2 at 2.12 cubic meters per hour (75 CFH)
Cup size No. 10 (slightly enlarged)
Contact tip bore - 2.06×10^{-3}m (8.1×10^{2} in.) diameter
Cup-to-work distance - 2.43×10^{-2} to 0.95×10^{-2}m (23/24 to 3/8 inch)
Contact tip recess in cup - 0.48×10^{-2}m (3/16 inch)
Welding current - 300 amps
Arc Voltage - 28.5 volts
Wire Feed Speed - 8.63m per min (340 ipm)

On the 62nd day after coating, panels 105106 through 117118 were welded. As indicated in Table I, some difficulty was experienced in the tapered incomplete penetration region of passes identified with a double asterisk. It was found that the torch lead angle was set at 0.105 radian (6 deg) rather than the previously used 0.087 radian (5 deg) lead angle. Since the arc is quite harsh in the tapered region, a very slight unbalance of the settings can cause arc gouging to occur. Therefore, the torch lead angle was reduced to 0.070 radian

(4 deg) for the remaining welds and the arc gouging disturbance was eliminated. The complete panels were subsequently shaved to within 2.54×10^{-4} m (1×10^{-2} in.) of the panel surface on both sides and submitted for nondestructive inspection.

3.4 NONDESTRUCTIVE INSPECTION

The 10 control panels were inspected by film radiography using the following parameters:

kv -	100
ma -	15
exposure -	2 minutes
ffd -	1.52 m (60 in.)
film -	Kodak 70 mm M, with lead screen
equipment -	Norelco constant potential, 300 kv maximum

Examination of the x-ray film showed only limited indication of the intentional incomplete penetration zone. These indications appeared on the end of the panel at the start of the weldment. In no case was there any indication of the incomplete penetration beyond 0.051 m (2 in.) from the end of the panel. Figure 2 shows a typical example of the x-ray film indications obtained.

In addition to the x-ray inspection, ultrasonic tests were conducted on the 10 control panels. Manual shear-wave tests were made to detect the incomplete penetration defects. In those areas which were seen on the x-ray film, the manual shear-wave approach was able to obtain a clear signal from the unwelded interface. All these indications were within 0.051 m (2 in.) of the ends of the panels.

Neither the x-ray or ultrasonic shear wave techniques were able to detect any incomplete penetration over 0.051 m (2 in.) from the end of any panel nor in the area of transition from partial penetration to full penetration weldment. To verify that these defects were present, several tensile specimens were cut from these areas. Figure 3 shows the fracture surfaces of two specimens which indicate clearly the areas of incomplete penetration. Both of these specimens were taken from areas which gave no indication whatever (by x-ray or ultrasonic techniques) of the defect condition present.

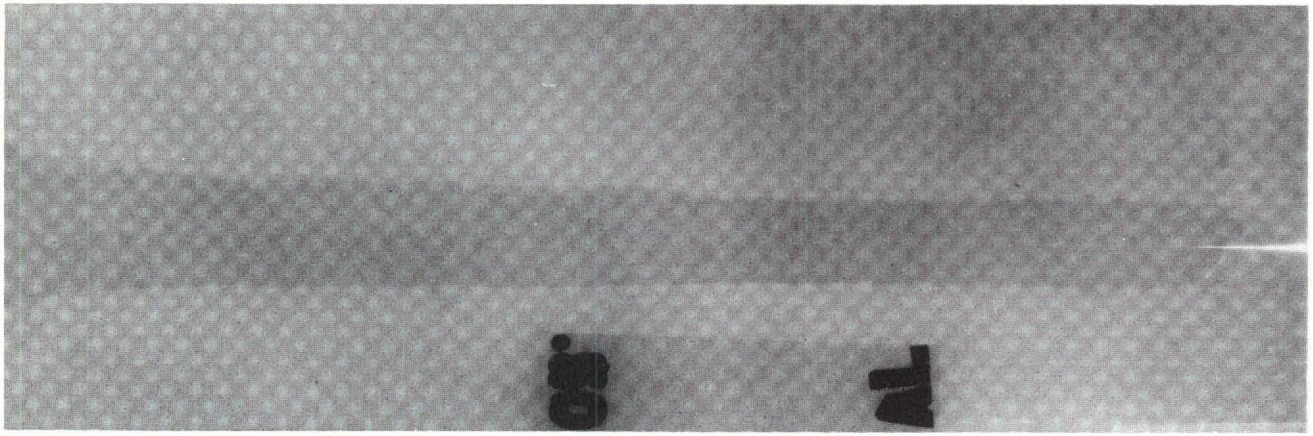


Figure 2. X-Ray Positive Print of Panel 8182 Zone of Incomplete Penetration

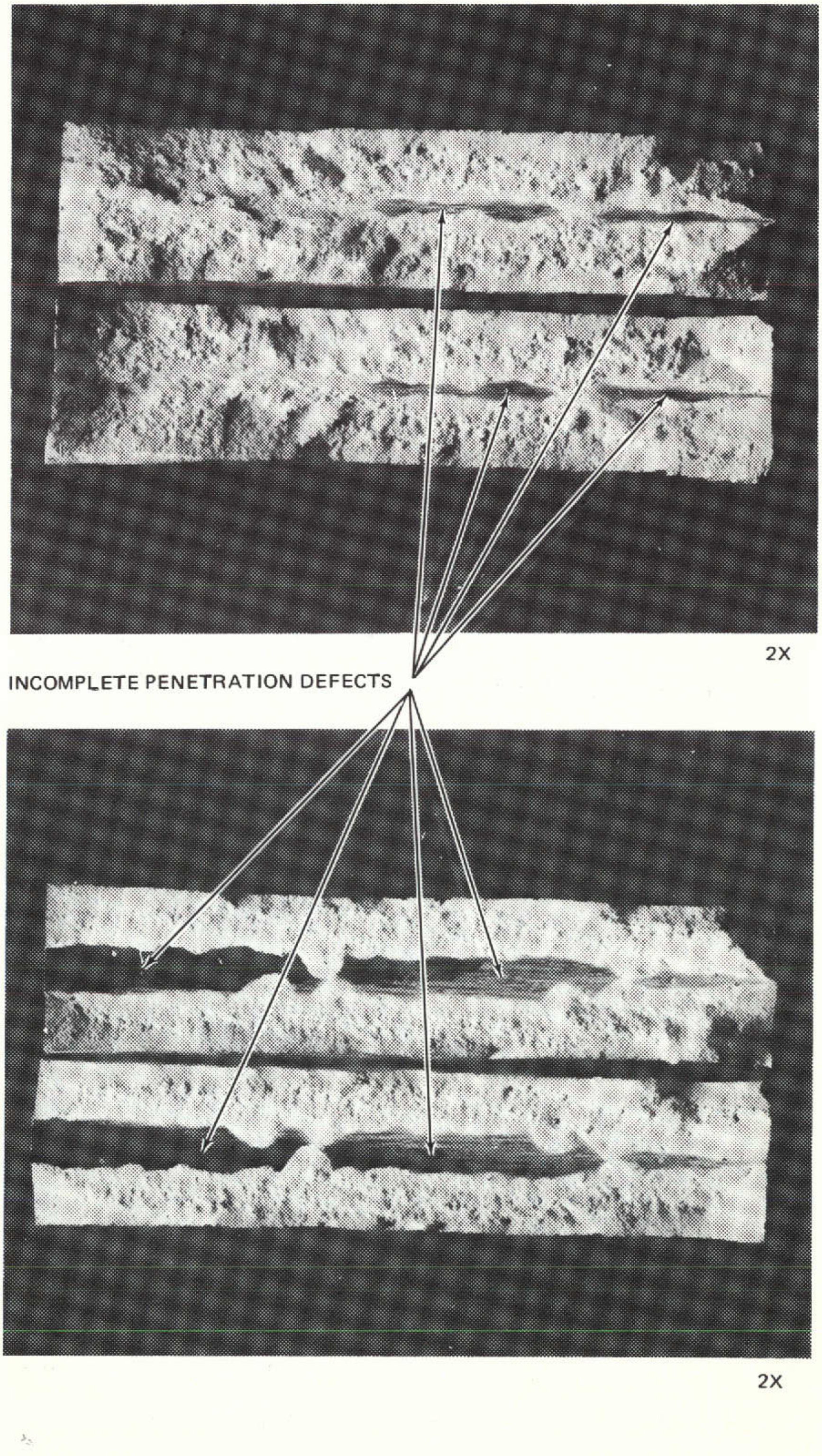


Figure 3. Fracture Surfaces of Two Tensile Specimens Taken from Zone of Incomplete Penetration on Panel 135136

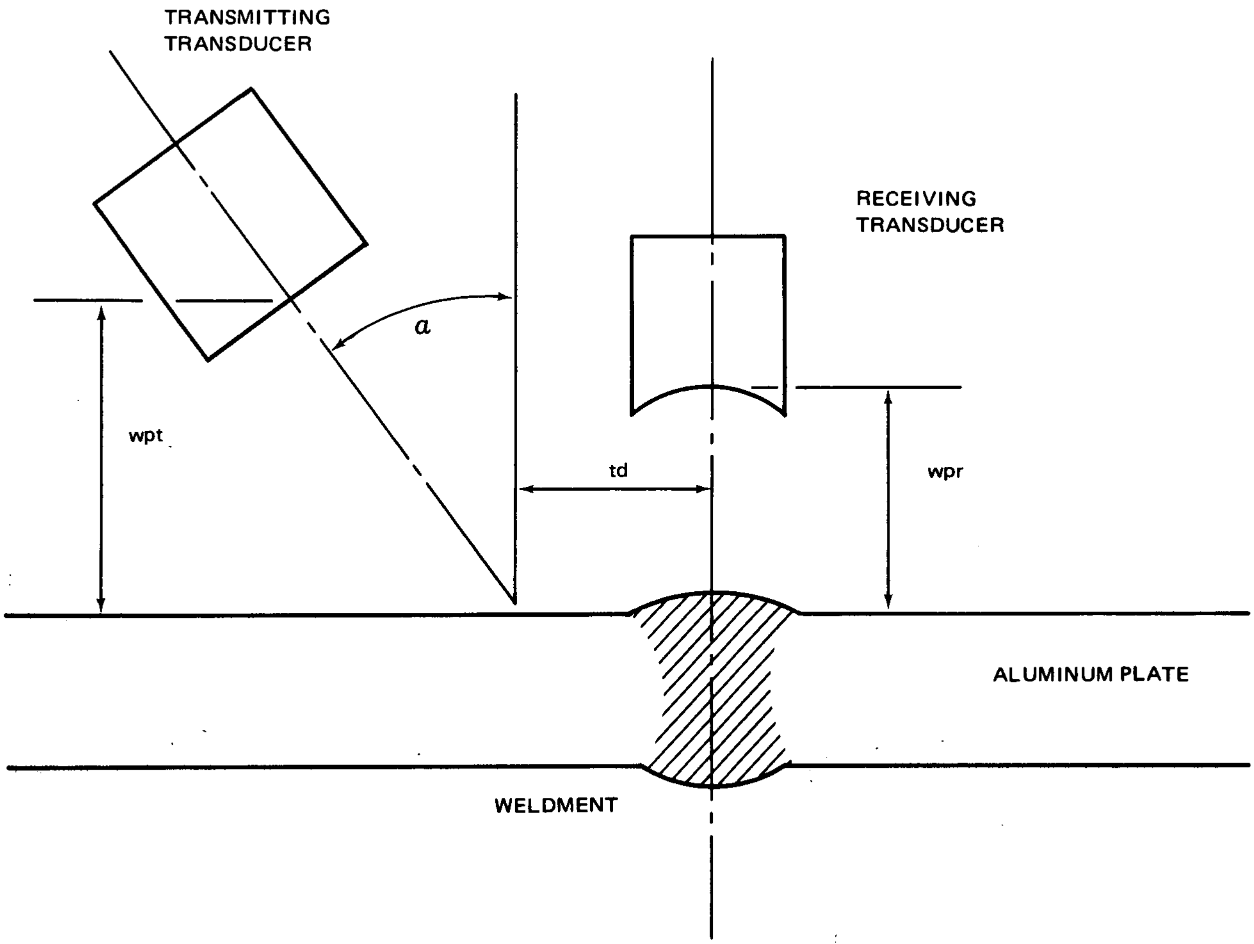
One control panel which had provided strong signals during the shear-wave inspection was investigated using the Delta approach. The immersed testing arrangement is shown in Figure 4. The test parameters were extracted from previous work (Reference 4) and the panel was manually scanned in the weldment area while observing the oscilloscope display.

The Delta technique did provide indication of the incomplete penetration defect, but only in those areas where the x-ray and shear-wave tests had also indicated a defect present. The incomplete penetration near the transition zone between incomplete and full penetration weldment could not be discerned.

While the weld bead had been machined to within 2.54×10^{-4} m (1×10^{-2} in.) of the parent plate surface, the surface of the weldment was not perfectly smooth, and there were signals coming from the weldment which made the data difficult to understand. Review of some of the available literature (Reference 5) on ultrasonic Delta techniques indicated that a very smooth surface was necessary for the approach to work. Direct contact was made with two organizations (References 6 and 7) experienced in Delta work. Both indicated that surface finish was a critical factor and that roughness remaining after removal of the weld heads made the approach impractical.

It was also indicated that high instrumentation sensitivity was necessary which also compounded the problem of a noisy background.

The 20 welded panels (from plates which were copper coated) were inspected using the same radiographic technique as used on the control panels. Examination of the x-ray film showed clear indication of the copper remaining in the zone of incomplete penetration. In several panels, the attempt at a tapered incomplete penetration defect resulted in intermittent penetration. This is shown very clearly by the presence of the copper, as seen in Figure 5. A typical transition from incomplete to full penetration weldment is seen in Figure 6. It is very obvious that the copper provides an extremely clear indication of the incomplete penetration defect. This is quite important since incomplete penetration defects are virtually impossible to detect by either radiography or ultrasonic techniques, as shown in the tests on the control panels.



VALUES FOR TEST ARRANGEMENT

a = 0.428 RADIANS (24.5°)
wpt = 0.035 METER (1–3/8 IN.)
td = 0.011 METER (7/16 IN.)
wpr = 0.041 METER (1–5/8 IN.)

Figure 4. Immersed Delta-Scan Test Arrangement Including Parameters Used in Tests for Incomplete Penetration of Aluminum Weldments (Reference No. 4)

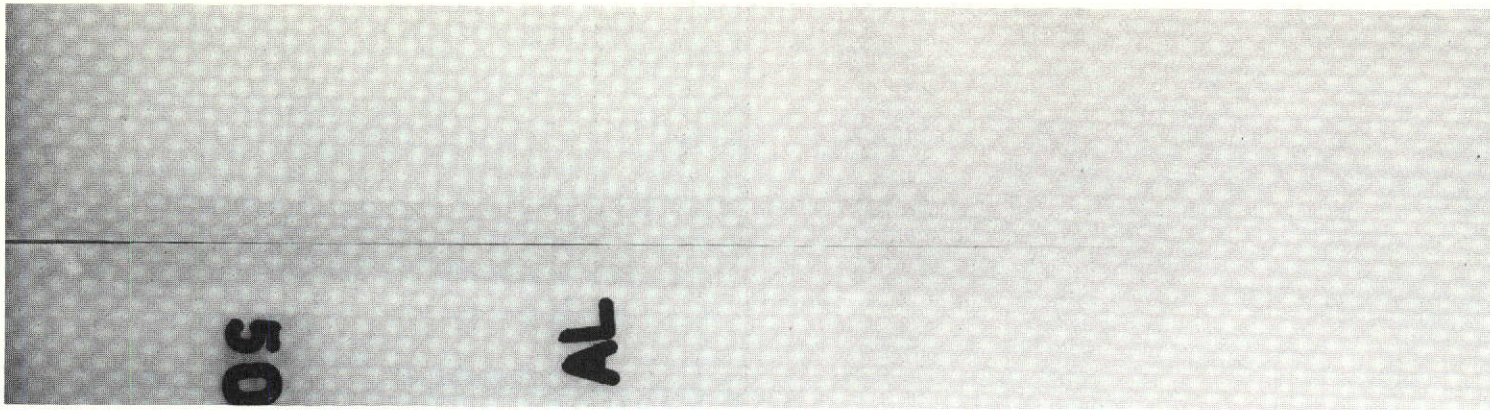


Figure 5. X-Ray Positive Print of Panel 107108 Showing Intermittent Incomplete Penetration

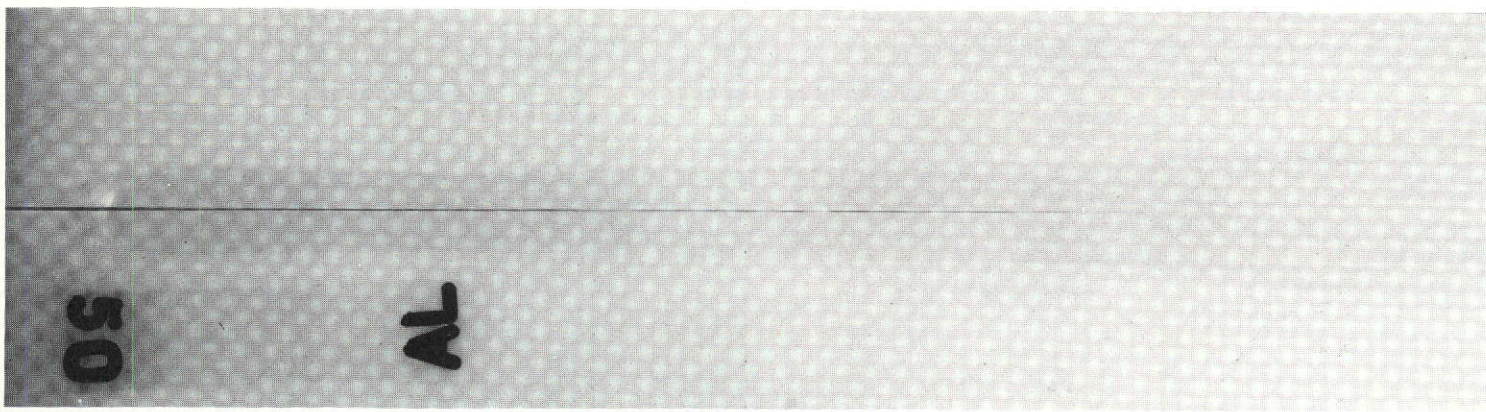


Figure 6. X-Ray Positive Print of Panel 3940 Showing Continuous Incomplete Penetration

Attempts to employ the ultrasonic Delta technique on weldments containing the copper additive were generally unsuccessful. Only those areas which were very near the end of the welded panel could be seen among all the signals from the weldment. In no case was it possible to pick up any signals near the transition from incomplete to full penetration weldment.

With the clear success of the copper additive as a means of detecting incomplete penetration, it does not seem worthwhile to pursue a less discriminating approach, such as Delta-scan. While Delta certainly has its applications, in this case such an immersed ultrasonic technique requiring special specimen surface conditions and very high instrumentation sensitivity does not seem the logical approach.

3.5 MECHANICAL PROPERTIES TESTING

The welded panels were all coded with four- or six-digit numbers derived from the original panel numbers. All tensile and bend test specimens were numbered using the welded panel code plus the letters "T" for tensile and "B" for bend.

The tensile specimens were constant-section and were cut approximately 0.058-m (2-in.) wide. The bend specimens were cut approximately 0.019-m (0.75-in.) wide. The length of all specimens was 0.305 m (12 in.), which was the width of all the welded panels.

The tensile tests were conducted on a Baldwin Universal Testing Machine of 266,880 N (60,000 lb) maximum capacity. The tests were conducted measuring load and strain, both of which were recorded autographically as the test was conducted. A 0.0508-m (2-in.) gage length breakaway extensometer was employed. The extensometer is a multiple-magnification instrument; the elastic portion of the recording can be made at a high magnification and the remainder at a lower magnification. This permitted recording of the complete load-versus-strain curve from start to failure.

Table 2

AVERAGES OF TENSILE TEST DATA - CONTROL PANELS (NO COPPER ADDED)

Panel No.	Yield Strength N/m^2	Yield Strength psi	Ultimate Strength N/m^2	Ultimate Strength psi	% Elongation 0.0508 m (2 in.)
7778	143.7×10^6	20.9×10^3	268.4×10^6	38.9×10^3	6
7980	153.7×10^6	22.6×10^3	264.8×10^6	38.4×10^3	6
8182	149.1×10^6	21.7×10^3	271.4×10^6	39.4×10^3	6
8384	149.8×10^6	21.8×10^3	266.5×10^6	38.7×10^3	6
8586	146.2×10^6	21.2×10^3	259.2×10^6	37.6×10^3	6
Average of all transverse weldments	148.5×10^6	21.6×10^3	266.0×10^6	38.6×10^3	6
133134	148.0×10^6	21.5×10^3	260.3×10^6	37.8×10^3	6
135136	149.2×10^6	21.6×10^3	255.7×10^6	37.1×10^3	6
139140	144.7×10^6	21.0×10^3	256.5×10^6	37.2×10^3	6
141142	131.5×10^6	19.1×10^3	258.2×10^6	37.5×10^3	6
Average of all longitudinal weldments	143.3×10^6	20.8×10^3	257.6×10^6	37.4×10^3	6

The average results of the tensile tests of the control specimens from panel 0102 are presented in Table 2. The average results of the tensile tests of the weldments made with copper deposited on the faying surfaces are presented in Table 3. The complete individual specimen data is shown in Tables A-1 and A-2 of the Appendix.

Table 3

AVERAGES OF TENSILE SPECIMENS FROM TEST PANELS WITH COPPER ADDED

Weldments Transverse to Plate Rolling Direction

Panel Code	Yield N/m^2	Yield psi	Ultimate N/m^2	Ultimate psi	% Elongation 0.0508m (2 in.)
3738	151.5×10^6	22.0×10^3	264.9×10^6	38.5×10^3	5.8
3940	143.4×10^6	20.8×10^3	262.8×10^6	38.1×10^3	5.8
4142	143.8×10^6	20.9×10^3	263.4×10^6	38.2×10^3	6.0
4344	146.4×10^6	21.3×10^3	263.0×10^6	38.2×10^3	6.0
4546	150.3×10^6	21.8×10^3	267.0×10^6	38.8×10^3	6.3
4748	140.8×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.5
4950	149.5×10^6	21.7×10^3	258.2×10^6	37.5×10^3	5.8
5152	144.3×10^6	21.0×10^3	265.8×10^6	38.6×10^3	6.0
5354	143.1×10^6	20.8×10^3	267.4×10^6	38.8×10^3	6.3
5556	144.9×10^6	21.0×10^3	261.9×10^6	38.0×10^3	6.3
Average	145.8×10^6	21.2×10^3	263.4×10^6	38.2×10^3	6.0

Weldments Parallel to Plate Rolling Direction

Panel Code	Yield N/m^2	Yield psi	Ultimate N/m^2	Ultimate psi	% Elongation 0.0508m (2 in.)
99100	140.1×10^6	20.4×10^3	261.3×10^6	37.9×10^3	6.5
101102	147.0×10^6	21.3×10^3	260.0×10^6	37.7×10^3	6.5
103104	141.1×10^6	20.5×10^3	253.7×10^6	36.8×10^3	6.0
105106	153.8×10^6	22.3×10^3	278.0×10^6	40.4×10^3	6.5
107108	141.1×10^6	20.5×10^3	266.3×10^6	38.6×10^3	6.0
109110	151.5×10^6	22.0×10^3	275.0×10^6	39.9×10^3	6.0
111112	148.0×10^6	21.5×10^3	251.9×10^6	36.6×10^3	5.3
113114	140.6×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.3
115116	142.6×10^6	20.7×10^3	271.0×10^6	39.4×10^3	6.0
117118	147.6×10^6	21.4×10^3	271.3×10^6	39.4×10^3	6.0
Average	145.3×10^6	21.1×10^3	264.8×10^6	38.4×10^3	6.0

The bend tests were conducted in a 266, 880 N (60, 000 lb) maximum capacity universal testing machine, in accordance with ASTM E16-64, Standard Method of Free Bend Test for Ductility of Welds. However, all specimens failed, developing cracks in the weldment and sharp load reductions during the initial "prebending" procedure. This occurred in both groups of specimens, the control group which had no copper added, and the remainder of samples which were taken from the panels having copper on the faying surfaces.

Average data from the control group are presented in Table 4; the average data from the group having a copper additive are presented in Table 5. The complete individual specimen data is shown in Tables A3 and A4 of the Appendix. In all cases, the failure loads were slightly higher for those specimens containing the copper additive. However, the percent elongations were slightly less and the included angles somewhat greater. This indicates a slight decrease in ductility for the weldments containing added copper.

The statistical evaluation was based on tensile yield (0. 2 percent offset) data which has been presented in Tables 2 and 3.

It was necessary to determine if the addition of copper had caused a significant change in the mechanical properties of the weldments. Calculations were made to determine whether there was a significant difference between the means of the two samples.

The value of the t statistic was calculated by the formula:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^{1/2}} \qquad \text{(Reference 8)}$$

where $\overline{X}$ = the mean of a sample

S^2 = variance of a sample

n = number of specimens in a sample

Table 4

AVERAGES OF BEND TEST DATA - CONTROL PANELS
(NO COPPER ADDED)

Panel No.	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0508 m (1/2 in.)
7778	14,439	3,246	2.487	142.5	29
7980	13,967	3,140	2.541	145.6	29
8182	13,733	3,088	2.509	143.8	26
8384	14,595	3,281	2.444	140.0	32
8586	14,189	3,190	2.476	141.9	27
Average of all transverse weldments	14,185	3,189	2.491	142.8	29
133134	12,777	2,873	2.476	141.9	28
135136	14,367	3,230	2.448	140.3	28
139140	12,620	2,838	2.467	141.4	27
141142	12,726	2,760	2.487	142.5	24
Average of all longitudinal weldments	13,123	2,925	2.470	141.5	27

The resulting value of t is then compared to those obtained from a t table (Reference 9). The degree of freedom is calculated by the formula:

$$\text{d.f.} = \left[\frac{C^2}{n_1 - 1} + \frac{(1 - C)^2}{n_2 - 1}\right]^{-1}$$

(Reference 8)

Table 5

AVERAGES OF BEND SPECIMENS FROM TEST PANELS
WITH COPPER ADDED

Weldments Transverse to Plate Rolling Direction

Panel Number	Failure Load		Included Angle		% Elongation 0.0127 m (1/2 in.)
	Newtons	Pounds	Radians	Degrees	
3738	15,368	3,455	2.548	146	26
3940	14,384	3,234	2.613	150	23
4142	15,271	3,433	2.563	147	25
4344	15,123	3,400	2.570	147	21
4546	15,357	3,453	2.530	145	24
4748	14,167	3,185	2.544	146	25
4950	14,678	3,300	2.535	145	25
5152	14,245	3,203	2.478	142	28
5354	14,390	3,235	2.570	147	21
5556	14,462	3,251	2.509	144	28
Average	14,745	3,315	2.546	146	25
	Weldments Parallel to Plate Rolling Direction				
99100	13,105	2,946	2.578	148	23
101102	13,711	3,083	2.504	144	22
103104	13,289	2,988	2.583	148	23
105106	14,295	3,214	2.426	139	29
107108	14,017	3,151	2.530	145	23
109110	13,806	3,104	2.539	146	23
111112	14,006	3,149	2.482	142	28
113114	14,272	3,209	2.513	144	25
115116	13,594	3,056	2.535	145	25
117118	14,462	3,251	2.508	144	26
Average	13,856	3,115	2.520	145	25

where the value of C is calculated by:

$$C = \frac{S_1^2/n_1}{S_1^2/n_1 + S_2^2/n_2} \qquad \text{(Reference 8)}$$

Comparisons were made between control and copper coated panels for weldments transverse to the original plate rolling direction, and for weldments parallel to the plate rolling direction. The calculated t values and degrees of freedom are given below:

Transverse weldments:	t = 1.04	d.f. = 13
Parallel weldments:	t = 0.704	d.f. = 10

In each case, the values were less than those listed at the 5-percent level of significance. Therefore, it may be stated that the means of the two samples were not significantly different at the 5-percent level of significance. It can be concluded that the addition of 5.08×10^{-6} m (2×10^{-4} in.) of copper to the faying surfaces to be welded has not caused any significant change in the properties.

3.6 PEEN PLATING INVESTIGATION

Peen plating is the deposition of one metal upon another by the peening action of glass shot. In practice, metal powder is mixed with glass shot and the mixture is propelled at high velocity against the surface to be coated by compressed gas. The metal powder is literally "hammered" into the receiving surface.

Once it had been established during the Phase I effort that the copper additive concept was successful, it was necessary to investigate means of copper application which were rapid and inexpensive. Peen plating of one metal on another had been investigated by NASA personnel at Lewis Research Center (Reference 9).

A review was made of the NASA patent disclosure regarding peen plating. The following items summarize the technical details of the disclosure.

A. Peening particle (glass bead) size may range from 2.54×10^{-5}-m (1×10^{-3}-in.) to 1.78×10^{-3}-m (7×10^{-2}-in.) diameter. For large, thick substrates, even larger beads could be employed, up to 2.54×10^{-3}-m (1×10^{-1}-in.) diameter.

B. The metallic powder size should be no greater than one half the peening bead size. The thinner the desired coating, the smaller the ratio of metal powder size to peening bead size.

C. The mixture of peening beads to metal powder should be approximately one-to-one if the emphasis is on coating. A greater fraction of metal powder than this is probably not efficient.

D. Experimental work indicates that a 0.0262-m (3-in.^{2}) area can be coated to a thickness of 2.54×10^{-5}-m (1×10^{-3}-in.) in approximately 30 seconds.

It was established that the facilities were available within the corporation for conducting the peen plating investigation. A small S. S. White Abrasive unit was available, and this was used for the preliminary feasibility tests. Although the unit is designed for abrasive cutting and surface cleaning and is effective over only a very small surface area, it was considered sufficient for the first tests.

Copper powder and glass beads were procured. Five pounds of copper powder, -170 +325 mesh and 99.9 percent pure, were obtained. Four pounds of glass beads were obtained, in the size range 14.99×10^{-5} to 24.89×10^{-5}-m (5.9×10^{-3} to 9.8×10^{-3}-in.) diameter. The copper powder size range is approximately 12.7×10^{-5} to 5.08×10^{-5}-m (5×10^{-3} to 2×10^{-3}-in.) and on the average about one-half the size of the glass beads. This is one of the conditions necessary (Reference No. 9) for successful plating by this method.

The tests were conducted on several small hand-held aluminum samples. The surfaces were cleaned using emery paper and then rinsed with MEK. Only a very small surface area was treated, approximately 0.0064-in. (1/4-in.) square. The nozzle on the Airbrasive unit was approximately 7.62×10^{-4}-in. (0.030 in.) diameter, and consequently the rate of deposition was quite slow.

The ratio of glass beads to copper powder was listed as one-to-one by the NASA disclosure (Reference 9). However, it was not clear whether this was on a weight or volume basis. Therefore, both approaches were tried. Samples were peen plated with both mixture ratios; one-to-one by weight and one-to-one by volume.

The one-to-one by weight combination appeared to provide the best and most uniform coverage of the samples. Because of the difference in material density, the volume of glass beads was over three times greater than the copper. This apparently resulted in more rapid deposition and retention of copper on the aluminum surface. Subsequent to the peening tests, the samples were sectioned and observed under a microscope to assess copper coverage and thickness. Figure 7 shows the section coated with the one-to-one by weight mixture of copper and glass beads. Figure 8 shows the section coated with the one-to-one by volume mixture. While neither section is ideal, Figure 7 shows the best surface coverage and thickest copper deposit. Because of the lack of a one to one correspondence of parameters in scaling up the process from the laboratory to a shop system (large nozzle), it was decided to conduct subsequent studies with the shop system.

The next series of tests was conducted in the glass bead peening facilities at the Douglas Aircraft Company plant in Torrance, California. A mixture of 22.7 kg (50 lb) each of copper powder and glass beads was placed in the peening unit which had a nozzle 9.5×10^{-3} m (3/8 in.) in diameter.

Four samples, 0.03 by 0.05 m (1 x 2 in.), were peen plated at four different times; 30 seconds, 1 minute, 2 minutes and 4 minutes. The holding chamber of the abrasive blasting equipment was loaded with 22.7 kg (50 lb) each of copper powder and glass beads. The unit was then started and allowed to run for several minutes to mix the load of copper and beads. Even then, however, there was visual evidence of uneven flow from the nozzle. Periodically, the color of the stream would change to more copper color, indicating that the copper was not mixing uniformly as the recycled material settled to the bottom of the reservoir below the blast chamber. This did not seem to affect the appearance of the sample surface however. In all tests, the aluminum surface appeared satiny without any indication of a copper color. The surface also appeared very uniform in shade and texture.

CR 76
N/A

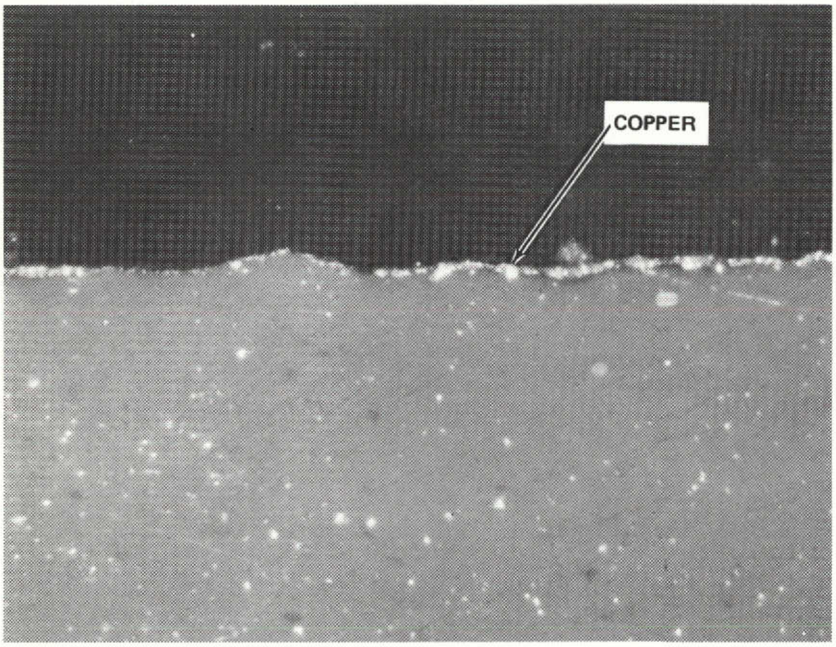


Figure 7. Copper Coating on Peen Plated Aluminum Sample (400X) Using One-to-One by Weight Mixture of Glass Beads and Copper Powder

CR 76
N/A

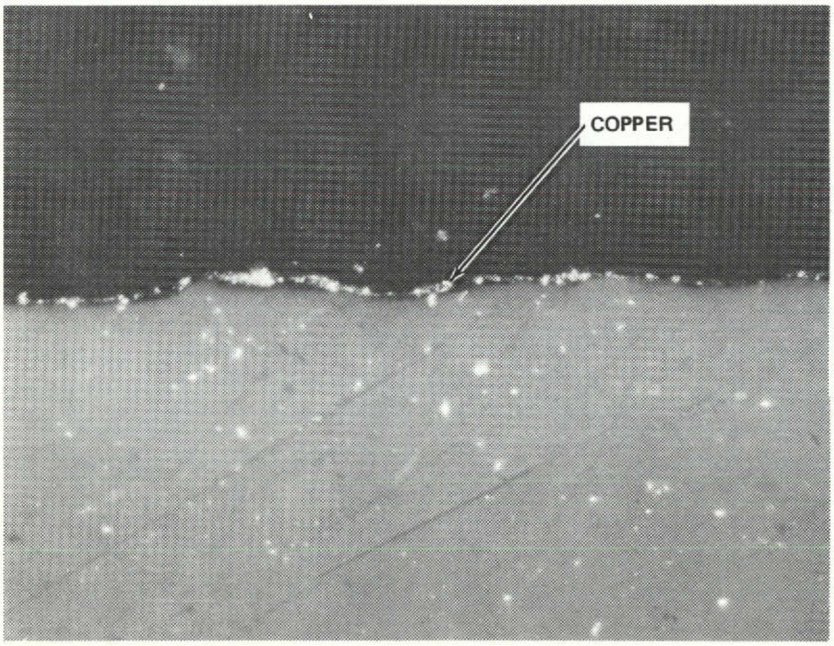


Figure 8. Copper Coating on Peen Plated Aluminum Sample (400X) Using One-to-One by Volume Mixture of Glass Beads and Copper Powder

In addition to the four small samples, four plate specimens were peened along one edge. These samples were 0.3-m (12-in.) long by 0.05-m (2-in.) wide by 0.01-m (0.5-in.) thick. They were peened on one 0.3-m (12-in.) by 0.01-m (0.5-in.) edge for 3 minutes.

These peen plating tests were not as successful as had been anticipated. Cross sections of the four small specimens showed very little copper at all. Only on the specimen exposed for four minutes was there any clear indication of copper on the surface, and these areas were very limited.

Unfortunately, the limited scope of the program precluded further testing and any attempt to optimize the application parameters. Certainly a careful and more detailed study of peening variables might be expected to produce more satisfactory results.

There are several technical factors which could account for the failure of the work with the larger nozzle system. The air pressure behind the nozzle was 85 psi, and this may have been too high. The high air pressure may have imparted a velocity too high to the stream of shot and copper powder. This could have resulted in the copper powder bouncing off the surface before the glass beads could effect the peening action. The remedy to this would be to reduce the air pressure to a lower value, thereby reducing the velocity of the stream of particles.

Another factor which is probably very critical is the ratio of glass bead size to copper powder size. It may be that the smaller the copper powder size with respect to bead size, the more effective the plating action. Since the glass bead must peen the copper onto the surface, it must be large enough to flatten the copper particle and cause it to hold to the surface until another bead can come along and continue the job. If the copper powder particle is relatively large, it offers more resistance to the peening action and may be more easily dislodged or deflected away from the surface.

The third factor is the amount of peening beads with respect to the copper powder. Higher ratios of glass beads would probably provide a more rapid builup of copper on the surface since any given particle of copper would be peened into place more effectively and rapidly.

While these peen plating experiments were not totally successful, they have pointed to some of the critical factors which must be explored during further work in this area.

Despite the marginal results of the peen plating effort, it is still an interesting and attractive approach to depositing copper on aluminum. In contrast to the requirements for vacuum vapor deposition, peen plating requires no vacuum, no seals, no special environment, no heat, and no super-critical cleaning procedures. The equipment is relatively inexpensive and can be run with compressed air. Ideally, the system should employ a separate means of introducing the peening beads and the copper powder. In this way, better control can be maintained on the mixture of the two. Further investigations of the specific application parameters should be made as rapidly as possible.

Section 4
DISCUSSION AND CONCLUSIONS

Results of the Phase II effort prove beyond any doubt the applicability of the opaque additive concept to aluminum weldment inspection. When thick section weldments require passes from each surface, the possibility of an incomplete penetration defect exists. It has been clearly shown by this work and past efforts (Reference 1) that such buried defects are virtually impossible to detect during inspection. The addition of copper to the faying surfaces, however, enhances the x-ray inspections. Visual interpretation of the x-ray film is very easy; any areas of incomplete penetration are clearly shown.

Application of the opaque additive concept depends upon some reasonable means of applying the copper to the faying surfaces of the two members to be welded. In this program, vacuum vapor deposition was employed and worked very well. This approach provides a very smooth, uniform copper layer that can be applied in very thin sections. The only problem with this approach is in the equipment and procedures for applying the copper. A vacuum system and a means of heating the copper to the molten state must be provided. Stationary equipment limits the size of the parts to be coated. Portable and sliding seal equipment has been developed and used and could conceivably be adapted to vacuum vapor deposition requirements of copper on aluminum.

It seems that another less complex approach to copper deposition on aluminum should be available. This program explored the possibility of employing peen plating as a means of applying the copper. The work showed that copper can be peened on aluminum, although the resultant coating was not uniform and did not provide complete coverage. Sufficient information to determine optimum stream velocity, bead and particle size, and quantity ratios of glass beads to copper powder was not obtained. Therefore, it was not possible to make any prediction of actual deposition rates. Clearly, more work needs to be done in this area, and as rapidly as possible.

However, the peen plating approach does appear to be a viable means of applying an opaque additive to faying surfaces of large structural members prior to welding. The peen plating process is extremely simple. There are no atmosphere requirements, no heating requirements, no vacuum seals, and no severe cleaning criteria. The only critical items are a means of introducing the glass beads and copper powder into the air stream separately, and a particle and dust retention and collecting system capable of moving along the edge of a large structural panel. The cost of such a system should be minor. This approach appears within the current state of the art, but requires additional effort to make it applicable on a practical basis.

Based upon the work conducted in this program and the factors which have been discussed, several significant conclusions can be made.

1. Film radiography of weldments can be significantly enhanced by addition of a very thin copper coating, 5.08×10^{-6} m (2×10^{-4} in.) on each faying surface. The appearance of incomplete penetration defects is very distinct on the x-ray film.
2. There are no significant effects in alloy chemistry or mechanical properties as a result of the addition of copper to the weldment.
3. Peen plating is a simple, viable approach worthy of further study. Additional effort is needed to develop efficient application practice.

Section 5
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Appendix
TEST DATA

The appendix presents the complete tensile and bend test data (Tables A-1 through A-4) for both the control welded panels and the welded panels containing copper as an opaque additive.

Table A-1

INDIVIDUAL SPECIMEN TENSILE DATA, CONTROL PANELS—PHASE II

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
7778T1	134.5×10^6	19.5×10^3	269.0×10^6	39.0×10^3	6
7778T2	152.9×10^6	22.2×10^3	267.8×10^6	38.8×10^3	6
Average	143.7×10^6	20.9×10^3	268.4×10^6	38.9×10^6	6
7980T1	153.6×10^6	22.8×10^3	264.9×10^6	38.4×10^3	6
7980T2	153.7×10^6	22.3×10^3	264.6×10^6	38.4×10^3	6
Average	153.7×10^6	22.6×10^3	264.8×10^6	38.4×10^3	6
8182T1	144.0×10^6	20.9×10^3	266.7×10^6	38.7×10^3	6
8182T2	154.2×10^6	22.4×10^3	276.0×10^6	40.0×10^3	6
Average	149.1×10^6	21.7×10^3	271.4×10^6	39.4×10^3	6
8384T1	141.8×10^6	20.6×10^3	249.8×10^6	36.2×10^3	6
8384T2	157.8×10^6	22.9×10^3	283.1×10^6	41.1×10^3	6
Average	149.8×10^6	21.8×10^3	266.5×10^6	38.7×10^3	6
8586T1	142.7×10^6	20.7×10^3	259.4×10^6	37.6×10^3	6
8586T2	149.6×10^6	21.7×10^3	259.0×10^6	37.6×10^3	
Average	146.2×10^6	21.2×10^3	259.2×10^6	37.6×10^3	6

Table A-1

INDIVIDUAL SPECIMEN TENSILE DATA, CONTROL PANELS—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
133134T1	147.2×10^6	21.4×10^3	255.2×10^6	37.0×10^3	6
133134T2	148.7×10^6	21.6×10^3	265.3×10^6	38.5×10^3	6
Average	148.0×10^6	21.5×10^3	260.3×10^6	37.8×10^3	6
135136T1	147.1×10^6	21.3×10^3	247.7×10^6	35.9×10^3	6
135136T2	151.3×10^6	21.9×10^3	263.6×10^6	38.2×10^3	6
Average	149.2×10^6	21.6×10^3	255.7×10^6	37.1×10^3	6
139140T1	142.4×10^6	20.7×10^3	250.0×10^6	36.3×10^3	6
139140T2	146.9×10^6	21.3×10^3	262.9×10^6	38.1×10^3	6
Average	144.7×10^6	21.0×10^3	256.5×10^6	37.2×10^3	6
141142T1	131.6×10^6	19.1×10^3	256.4×10^6	37.2×10^3	6
141142T2	131.3×10^6	19.1×10^3	259.9×10^6	37.7×10^3	6
Average	131.5×10^6	19.1×10^3	258.2×10^6	35.5×10^3	6

Table A-2

INDIVIDUAL SPECIMEN BEND DATA, CONTROL PANELS—PHASE II

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0127 m (1/2 in.)
7778B1	14,278	3,210	2.513	144.0	29
7778B2	14,678	3,300	2.513	144.0	29
7778B3	14,456	3,250	2.460	141.0	29
7778B4	14,345	3,225	2.460	141.0	30
Average	14,439	3,246	2.487	142.5	29
7980B1	13,900	3,125	2.548	146.0	29
7980B2	12,677	2,850	2.583	148.0	25
7980B3	14,723	3,310	2.574	147.5	29
7980B4	14,567	3,275	2.460	141.0	34
Average	13,967	3,140	2.541	145.6	29
8182B1	14,456	3,250	2.548	146.0	29
8182B2	13,522	3,040	2.548	146.0	25
8182B3	13,388	3,010	2.522	144.5	25
8182B4	13,566	3,050	2.417	138.5	25
Average	13,733	3,088	2.509	143.8	26
8384B1	14,567	3,275	2.460	141.0	30
8384B2	13,789	3,100	2.443	140.0	34
8384B3	15,234	3,425	2.382	136.5	34
8384B4	14,790	3,325	2.487	142.5	30
Average	14,595	3,281	2.444	140.0	32

Table A-2

INDIVIDUAL SPECIMEN BEND DATA, CONTROL PANELS—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0127m (1/2 in.)
8586B1	14,011	3,150	2.513	144.0	30
8586B2	14,456	3,250	2.426	139.0	25
8586B3	14,723	3,310	2.504	143.5	25
8586B4	13,566	3,050	2.460	141.0	29
Average	14,189	3,190	2.476	141.9	27
133134B1	12,410	2,790	2.443	140.0	25
133134B2	12,010	2,700	2.434	139.5	29
133134B3	14,011	3,150	2.504	143.5	29
133134B4	12,677	2,850	2.522	144.5	29
Average	12,777	2,873	2.476	141.9	28
135136B1	13,967	3,140	2.443	140.0	30
135136B2	14,634	3,290	2.391	137.0	30
135136B3	14,189	3,190	2.487	142.5	25
135136B4	14,678	3,300	2.469	141.5	25
Average	14,367	3,230	2.448	140.3	28
139140B1	12,561	2,825	2.495	143.0	25
139140B2	12,454	2,800	2.460	141.0	29
139140B3	12,232	2,750	2.443	140.0	25
139140B4	13,233	2,975	2.469	141.5	30
Average	12,620	2,838	2.467	141.4	27

Table A-2

INDIVIDUAL SPECIMEN BEND DATA,
CONTROL PANELS—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0127 m (1/2 in.)
141142B1	13,010	2,925	2.504	143.5	25
141142B2	12,454	2,800	2.522	144.5	21
141142B3	11,298	2,540	2.443	140.0	25
141142B4	12,343	2,775	2.478	142.0	25
Average	12,726	2,760	2.487	142.5	24

Table A-3

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
3738T1	149.1×10^6	21.6×10^3	268.4×10^6	38.9×10^3	6.0
3738T2	153.8×10^6	22.3×10^3	261.4×10^6	38.0×10^3	5.5
Average	151.5×10^6	22.0×10^3	264.9×10^6	38.5×10^3	5.8
3940T1	147.6×10^6	21.4×10^3	262.0×10^6	38.0×10^3	5.5
3940T2	139.2×10^6	20.2×10^3	263.5×10^6	38.2×10^3	6.0
Average	143.4×10^6	20.8×10^3	262.8×10^6	38.1×10^3	5.8
4142T1	144.4×10^6	20.9×10^3	262.0×10^6	38.0×10^3	6.0
4142T2	143.2×10^6	20.8×10^3	264.8×10^6	38.4×10^3	6.0
Average	143.8×10^6	20.9×10^3	263.4×10^6	38.2×10^3	6.0
4344T1	143.8×10^6	20.9×10^3	262.6×10^6	38.1×10^3	6.0
4344T2	148.9×10^6	21.6×10^3	263.4×10^6	38.2×10^3	6.0
Average	146.4×10^6	21.3×10^3	263.0×10^6	38.2×10^3	6.0
4546T1	148.9×10^6	21.6×10^3	265.3×10^6	38.5×10^3	6.5
4546T2	151.7×10^6	22.0×10^3	268.6×10^6	39.0×10^3	6.0
Average	150.3×10^6	21.8×10^3	267.0×10^6	38.8×10^3	6.3

Table A-3

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
4748T1	137.9×10^6	20.0×10^3	257.8×10^6	37.4×10^3	5.5
4748T2	143.6×10^6	20.8×10^3	261.9×10^6	38.0×10^3	5.5
Average	140.8×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.5
4950T1	145.9×10^6	21.2×10^3	259.7×10^6	37.7×10^3	5.5
4950T2	153.0×10^6	22.2×10^3	256.7×10^6	37.2×10^3	6.0
Average	149.5×10^6	21.7×10^3	258.2×10^6	37.5×10^3	5.8
5152T1	139.8×10^6	20.3×10^3	259.9×10^6	37.7×10^3	6.0
5152T2	148.7×10^6	21.6×10^3	271.7×10^6	39.4×10^3	6.0
Average	144.3×10^6	21.0×10^3	265.8×10^6	38.6×10^3	6.0
5354T1	139.7×10^6	20.3×10^3	266.8×10^6	38.7×10^3	6.0
5354T2	146.4×10^6	21.2×10^3	267.9×10^6	38.9×10^3	6.5
Average	143.1×10^6	20.8×10^3	267.4×10^6	38.8×10^3	6.3
5556T1	147.1×10^6	21.3×10^3	255.1×10^6	37.0×10^3	6.0
5556 T2	142.7×10^6	20.7×10^3	268.7×10^6	39.0×10^3	6.5
Average	144.9×10^6	21.0×10^3	261.9×10^6	38.0×10^3	6.3

Table A-3

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
99100T1	141.3×10^6	20.5×10^3	260.4×10^6	37.7×10^3	6.5
99100T2	138.9×10^6	20.2×10^3	262.1×10^6	38.0×10^3	6.5
Average	140.1×10^6	20.4×10^3	261.3×10^6	37.9×10^3	6.5
101102T1	-	-	260.6×10^6	37.8×10^3	6.5
101102T2	147.0×10^6	21.3×10^3	259.4×10^6	37.6×10^3	6.5
Average	147.0×10^6	21.3×10^3	260.0×10^6	37.7×10^3	6.5
103104T1	140.9×10^6	20.4×10^3	263.6×10^6	38.2×10^3	6.0
103104T2	141.3×10^6	20.5×10^3	243.7×10^6	35.4×10^3	6.0
Average	141.1×10^6	20.5×10^3	253.7×10^6	36.8×10^3	6.0
105106T1	154.3×10^6	22.4×10^3	277.0×10^6	40.2×10^3	6.5
105106T2	153.3×10^6	22.2×10^3	278.9×10^6	40.5×10^3	6.5
Average	153.8×10^6	22.3×10^3	278.0×10^6	40.4×10^3	6.5
107108T1	144.1×10^6	20.9×10^3	268.4×10^6	38.9×10^3	6.0
107108T2	138.0×10^6	20.0×10^3	264.2×10^6	38.3×10^3	6.0
Average	141.1×10^6	20.5×10^3	266.3×10^6	38.6×10^3	6.0

Table A-3

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
109110T1	150.9×10^6	21.9×10^3	276.4×10^6	40.1×10^3	6.0
109110T2	152.0×10^6	22.0×10^3	273.5×10^6	39.7×10^3	6.0
Average	151.5×10^6	22.0×10^3	275.0×10^6	39.9×10^3	6.0
111112T1	144.4×10^6	20.9×10^3	261.0×10^6	37.9×10^3	5.0
111112T2	151.5×10^6	22.0×10^3	242.8×10^6	35.2×10^3	5.5
Average	148.0×10^6	21.5×10^3	251.9×10^6	36.6×10^3	5.3
113114T1	139.2×10^6	20.2×10^3	262.9×10^6	38.1×10^3	5.5
113114T2	141.9×10^6	20.6×10^3	256.8×10^6	37.3×10^3	5.0
Average	140.6×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.3
115116T1	142.0×10^6	20.6×10^3	273.4×10^6	39.7×10^3	6.0
115116T2	143.1×10^6	20.8×10^3	268.6×10^6	39.0×10^3	6.0
Average	142.6×10^6	20.7×10^3	271.0×10^6	39.4×10^3	6.0
117118T1	146.2×10^6	21.2×10^3	263.4×10^6	38.2×10^3	6.0
117118T2	148.9×10^6	21.6×10^3	279.2×10^6	40.5×10^3	6.0
Average	147.6×10^6	21.4×10^3	271.3×10^6	39.4×10^3	6.0

Table A-4

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II

Specimen Code	Failure Load		Included Angle		% Elongation 0.0127m (1/2 in.)
	Newtons	lb	Radians	Degrees	
3738B1	14, 234	3, 200	2. 652	152	21
3738B2	15, 835	3, 560	2. 512	144	25
3738B3	15, 835	3, 560	2. 478	142	29
3738B4	15, 568	3, 500	2. 548	146	29
Average	15, 368	3, 455	2. 548	146	26
3940B1	12, 566	2, 825	2. 705	155	25
3940B2	15, 879	3, 570	2. 530	145	25
3940B3	14, 767	3, 320	2. 565	147	25
3940B4	14, 323	3, 220	2. 652	152	18
Average	14, 384	3, 234	2. 613	150	23
4142B1	-	-	-	-	-
4142B2	16, 013	3, 600	2. 460	141	30
4142B3	15, 234	3, 425	2. 548	146	25
4142B4	14, 567	3, 275	2. 687	154	21
Average	15, 271	3, 433	2. 565	147	25
4344B1	14, 122	3, 175	2. 722	156	15
4344B2	14, 901	3, 350	2. 513	144	18
4344B3	16, 013	3, 600	2. 513	144	25
4344B4	15, 457	3, 475	2. 530	145	25
Average	15, 123	3, 400	2. 570	147	21
4546B1	15, 435	3, 470	2. 548	146	25
4546B2	15, 346	3, 450	2. 495	143	21
4546B3	15, 346	3, 450	2. 495	143	29
4546B4	15, 301	3, 440	2. 583	148	21
Average	15, 357	3, 453	2. 530	145	24

Table A-4

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation 0.0127m (1/2 in.)
	Newtons	lb	Radians	Degrees	
4748B1	12, 899	2, 900	2. 670	153	22
4748B2	14, 234	3, 200	2. 635	151	20
4748B3	14, 634	3, 290	2. 443	140	28
4748B4	14, 901	3, 350	2. 426	139	28
Average	14, 167	3, 185	2. 544	146	25
4950B1	14, 189	3, 190	2. 565	147	25
4950B2	14, 901	3, 350	2. 478	142	29
4950B3	15, 123	3, 400	2. 495	143	25
4950B4	14, 500	3, 260	2. 600	149	21
Average	14, 678	3, 300	2. 535	145	25
5152B1	14, 589	3, 280	2. 443	140	28
5152B2	13, 566	3, 050	2. 635	151	24
5152B3	14, 589	3, 280	2. 338	134	30
5152B4	14, 234	3, 200	2. 495	143	30
Average	14, 245	3, 203	2. 478	142	28
5354B1	14, 545	3, 270	2. 565	147	24
5354B2	14, 545	3, 270	2. 548	146	24
5354B3	14, 234	3, 200	2. 565	147	16
5354B4	14, 234	3, 200	2. 600	149	18
Average	14, 390	3, 235	2. 570	147	21
5556B1	13, 300	2, 990	2. 670	153	21
5556B2	15, 123	3, 400	2. 426	139	30
5556B3	15, 012	3, 375	2. 408	138	34
5556B4	14, 412	3, 240	2. 530	145	25
Average	14, 462	3, 251	2. 509	144	28

Table A-4

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	lb	Radians	Degrees	0.0127 m (1/2 in.)
99100B1	11,231	2,525	2.687	154	22
99100B2	14,011	3,150	2.513	144	20
99100B3	13,878	3,120	2.530	145	24
99100B4	13,300	2,990	2.583	148	24
Average	13,105	2,946	2.578	148	23
101102B1	13,967	3,140	2.460	141	24
101102B2	14,056	3,160	2.443	140	22
101102B3	13,344	3,000	2.530	145	20
101102B4	13,477	3,030	2.583	148	20
Average	13,711	3,083	2.504	144	22
103104B1	12,410	2,790	2.583	148	21
103104B2	13,811	3,105	2.600	149	20
103104B3	13,811	3,105	2.513	144	26
103104B4	13,122	2,950	2.635	151	24
Average	13,289	2,988	2.583	148	23
105106B1	14,478	3,255	2.356	135	30
105106B2	14,367	3,230	2.408	138	30
105106B3	14,234	3,200	2.443	140	28
105106B4	14,100	3,170	2.495	143	26
Average	14,295	3,214	2.426	139	29
107108B1	12,810	2,880	2.722	156	15
107108B2	14,678	3,300	2.356	135	34
107108B3	14,234	3,200	2.530	145	18
107108B4	14,345	3,225	2.513	144	25
Average	14,017	3,151	2.530	145	23

Table A-4

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation 0.0127 m (1/2 in.)
	Newtons	lb	Radians	Degrees	
109110B1	13, 122	2, 950	2. 600	149	21
109110B2	14, 790	3, 325	2. 373	136	30
109110B3	13, 166	2, 960	2. 670	153	15
109110B4	14, 145	3, 180	2. 513	144	25
Average	13, 806	3, 104	2. 539	146	23
111112B1	14, 189	3, 190	2. 443	140	28
111112B2	13, 967	3, 140	2. 495	143	28
111112B3	13, 900	3, 125	2. 443	140	30
111112B4	13, 967	3, 140	2. 548	146	26
Average	14, 006	3, 149	2. 482	142	28
113114B1	14, 011	3, 150	2. 565	147	21
113114B2	14, 500	3, 260	2. 460	141	30
113114B3	14, 456	3, 250	2. 426	139	29
113114B4	14, 122	3, 175	2. 600	149	21
Average	14, 272	3, 209	2. 513	144	25
115116B1	12, 010	2, 700	2. 600	149	24
115116B2	14, 456	3, 250	2. 478	142	26
115116B3	14, 011	3, 150	2. 530	145	24
115116B4	13, 900	3, 125	2. 530	145	26
Average	13, 594	3, 056	2. 535	145	25
117118B1	13, 789	3, 100	2. 443	140	24
117118B2	15, 368	3, 455	2. 460	141	26
117118B3	14, 234	3, 200	2. 600	149	26
117118B4	14, 456	3, 250	2. 530	145	28
Average	14, 462	3, 251	2. 508	144	26